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ADVANCES IN ISENTROPIC COMPRESSION EXPERIMENTS (ICE) USING HIGH EXPLOSIVE PULSED POWER*

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Abstract

We are developing a prototype high explosive pulsed power (HEPP) system to obtain isentropic Equation of State (EOS) data with the Asay technique [1]. Our prototype system comprises a flat-plate explosive driven magnetic flux compression generator (FCG), an explosively formed fuse (EFF) opening switch, and a series of explosively-actuated closing switches. The FCG is capable of producing ~10 MA into suitable loads, and, at a length of 216 mm, the EFF will sustain voltages in excess of 200 kV. The load has an inductance of ~3 to 10 nH, allowing up to ~7 MA to be delivered in times of ~0.5 µs. This prototype will produce isentropic compression profiles in excess of 2 Mbar in a material such as tungsten. Our immediate plan is to obtain isentropic EOS data for copper at pressures up to ~1.5 Mbar with the prototype system; eventually we hope to reach several tens of Mbar with more advanced systems.

I. HEPP - ICE CONCEPT

A. Introduction

Smoothly rising (shock-free) mechanical compression waves (ramp waves) have been propagated into various samples by electromagnetic loading at pressures in excess of 1 Mbar. With this technique high quality isentropic (shock-free) EOS data have now been obtained for many materials, e.g., copper and tantalum [2]. ICE experiments have also been performed on insulating materials, even high explosives [3].

In a previous paper [4] we described early work on a compact, HEPP-ICE system, designed to perform the same ICE experiments, and to eventually extend the scope of the work to higher pressures. At that time we were unable to transfer currents in excess of 3 MA to the loads of interest, when 7 to 10 MA were required. In this paper we report on our progress, the problems we encountered, the solutions, and our ultimate successes in producing megabar ramp waves with the prototype HEPP-ICE system.

II. PRINCIPLES OF ICE

The physics of ICE and the methods of data recovery and analysis are described by Reisman [2]. The basic principle of ICE is the magnetic loading of a sample situated adjacent to a pair of parallel conductors, Fig. 1. If equal opposing currents per unit width flow in the conductors, J, then the magnetic pressure applied to the inside surfaces is $P_B = ½\mu_0 J^2$ in SI units. When $J = 5\times10^8$ A/m, the the magnetic pressure $P_B = 50\pi$ GPa (1.57 Mbar).

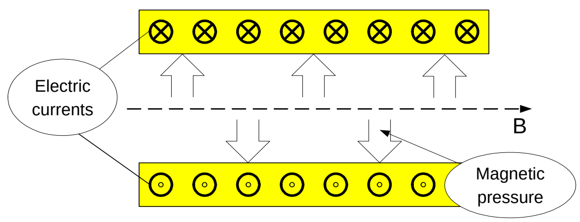

Figure 1. Magnetic forces between parallel conductors

If the time of application of these currents is short, compared to the time it takes a compression wave to traverse the conductor and back again, then the high pressures can be reached before the conductors have time to move apart and interrupt current flow. High pressure ramp waves eventually transition into shock waves if the pressure and distance of wave travel are large enough. The distance taken to shock-up depends on the pressure, the material of study, the dimensions of the sample, and the current rise time. Typical current rise times of the order of 500 ns are desirable for ICE experiments.

A. HEPP approach.

We have developed a prototype HEPP-ICE system using a compact explosive FCG, a storage inductor, and an EFF, capable of delivering 10 MA (dI/dt ~3×10^{13} A/s) into loads of 1 to 2 cm width with the required risetimes. This prototype is capable of developing ramp waves up to about 3 Mbar. (Eventually we plan to develop larger systems capable of developing ramp waves in the tens of megabars.) Much of the basic system was described previously [1], as well as our techniques used for modeling and predicting HEPP-ICE performance.

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1) System

The HEPP-ICE system comprises six basic components shown in Figure 2: a 12 mF, 20 kV capacitor bank; a flat-plate FCG; a storage inductor; an explosively formed fuse (EFF) [5]; a system of parallel closing switches; and the load. First the capacitor bank develops a seed current of ~1.9 MA in the circuit. The FCG then amplifies the seed current to a peak of 12 MA in a storage inductor of 25 to 50 nH, depending on the experiment. At peak current the EFF is opened and generates a voltage of 100 kV to 180 kV, according to the requirements of the experiment. Then three parallel closing switches are triggered simultaneously at the required voltage and current is transferred to the load. In this way currents of the order of 7 MA are transferred to loads of 5 to 10 nH in about 500 ns.

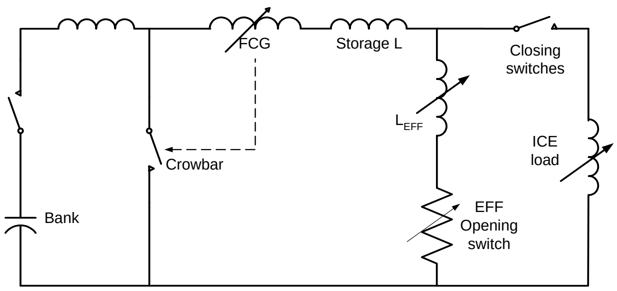


Figure 2. Basic HEPP-ICE circuit

2) EFF design.

The EFF was designed for 180 kV and 12 MA operation. It uses an annealed 1100-aluminum cylindrical conductor, 812 µm thick, 203.2-mm diameter and 223.5 mm long. The switch is driven by a 203.2-mm cylindrical PBX-9501 explosive charge, which is simultaneously detonated along its central axis. The switch die is a 225-mm diameter Teflon tube, with 24- 1.50 mm-wide anvils and 25- 6.00-mm spaces, over a total length of 223.5 mm; the cavity depths are 12.7 mm. The transmission line assembly, without the FCG, is shown in Fig. 3.

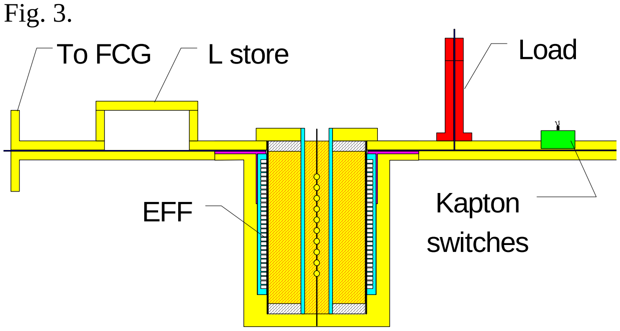


Figure 3. Sketch of assembly, minus FCG.

III. EXPERIMENTAL DESIGN

A. Causes of low current transfer

After many disappointing experiments, where we failed to transfer more than 3 MA to the load, we isolated the causes of the poor current transfer. First, we identified closing switch problems. The closing time of the Procyon-style switches [6] was strongly dependent on current, and the impedances of the switches were too large when they closed. Second, in an effort to correct the switch problem we inadvertently introduced a new breakdown problem in the Kapton insulation. These problems are described below. Fortunately, there were no significant problems with the FCG, the EFF, or the load.

B. Procyon closing switch timing problems

1) Voltage sensitivity of timing.

These switches had proven to be reliable and effective in previous HEPP experiments [6] so we had no reason to expect problems when they were used for HEPP-ICE. However, we found that the voltage across the switches dropped much more slowly in an ICE experiment than predicted using data from switch tests, i.e., the switches did not close correctly. To understand this we measured the time between triggering of the switches explosive system as a function of voltage over a series of tests. We found that the time to switch closure (from trigger time) fell by 500 ns when the voltage across the switch was increased from 20 kV to 140 kV, a range of voltages the switches might experience in an HEPP-ICE experiment. This is serious because 500 ns is comparable with the duration of an ICE experiment.

The initial impedance of the switch was estimated to be of the order of 10 nH, i.e., high for this application.

2) Effects on parallel switches.

When three switches are wired in parallel, and triggered simultaneously, it is inevitable that one switch will start to conduct first. This conduction lowers the voltage across the other two switches from perhaps 140 kV down to a few kV, depending on the impedances of the source and the switch. Because of the temporal sensitivity of the switch voltage, the other two switches now take 500 ns longer to conduct; in effect they remain open for nearly the full duration of the ICE experiment. In effect only one switch conducts and the transfer current is limited to ~3 MA by the inherent impedance of the single switch. So, the problem was that the Procyon switch, which functioned perfectly in the slower Procyon experiments, was unsuitable for sub-microsecond experiments like HEPP-ICE. It was clear that we needed a faster switch. Hence, we developed the Kapton switches described below.

3) Analysis of Procyon switch operation.

The basic design of the original switch is shown in Fig. 4. A pair of 1.27-cm diameter by 1.27-cm long, PBX-9407 high explosive (HE) pellets are inserted in a solid aluminum housing and detonated from the top. At the bottom is a thin aluminum disk with a ring cavity with a hemispherical cross-section. The switch operation has been modeled using the MESA hydrocode, without accounting for electromagnetic effects. From this we have found that the cavity produces a 1 km/s ring jet when shocked by the detonating explosive. The ring jet is projected into a 1.5-mm thick Mylar insulator and it is this penetration that closes the circuit.

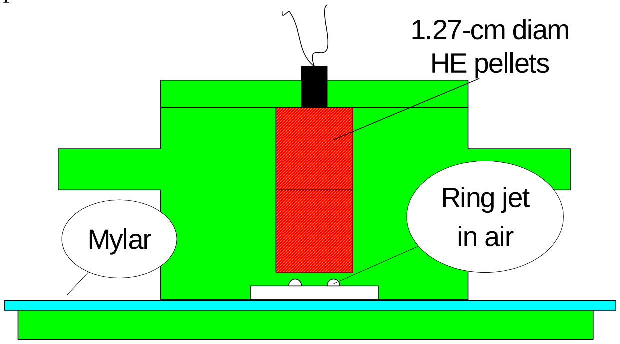


Figure 4. Procyon closing switch.

At 1 km/s, the jet takes 1.5 µs to traverse the Mylar. During that time shock waves are formed ahead of the jet in the Mylar at velocities of ≥2.5 km/s. When an electric field is applied, breakdown will occur before full penetration of the Mylar by the jet, probably in the pre-shocked and cracked Mylar. The larger the applied electric field, the shorter the distance of penetration by the jet that is necessary for breakdown to occur.

This explains the temporal sensitivity of the switch to voltage. Referring to the switch results above, at 140 kV the jet needs 500 ns less penetration distance (i.e., ½ mm) to induce breakdown than at 20 kV. In any case, filamentary breakdown occurs before full penetration of the jet through the Mylar and metal-to-metal contact, which explains the high initial impedance (~10 nH).

C. New closing switch design.

1) Kapton switch.

The Kapton switch is shown schematically in Fig. 5. We needed to design a faster switch, with a lower temporal sensitivity to voltage, lower temporal jitter, and a lower inductance. Our goals for the switch were a voltage sensitivity of ~50 ns from 120 kV to 20 kV, a jitter of ~20 ns, and an inductance < 1 nH. We decided to use shock induced conductivity in Kapton insulation as the conduction mechanism, for the following reasons. First, explosively driven shocks traverse Kapton at 5 to 6 km/s, five times faster than the Procyon jet; and this should improve temporal sensitivity to voltage and jitter.

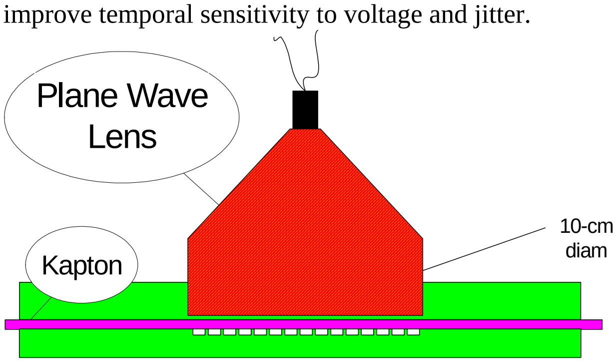


Figure 5. Kapton closing switch.

And with Kapton we could reduce the insulation thickness from 1.5 mm to 1.0 mm, for a further improvement in transit time. Second, by using shock-induced conduction over a broad area we could avoid or minimize filamentary conduction and reduce the inductance.

To reduce the switch impedance, we increased the explosive charge from 1.27-mm pellets to a 10-cm. diameter plane wave lens (P-100) and 10-cm diameter PBX-9501 booster; which are placed on top of the switch assembly. The explosives sit in an aluminum well, 3 mm above the 1.0-mm thickness of Kapton (typically as 20, 50-µm sheets).

2) Results.

We thoroughly tested this switch for temporal voltage sensitivity, jitter, and impedance. We found that the temporal sensitivity was down to 60 ns, the jitter to 25 ns, and the inductance was estimated to be ≤ 1 nH (the limit of our instrumentation accuracy). We had therefore met our design goals and were ready to use the switch in an HEPP-ICE experiment.

3) Air gaps in Kapton switch.

One disadvantage of the new Kapton switch was the problem of eliminating air between surfaces. For reliable operation it is essential that air gaps are excluded. These switches are designed for insertion in a parallel plate transmission line assembly, with dimensions of approximately 60 cm wide by 120 cm long. Unless great care is taken, it is difficult to keep these large surfaces flat and parallel to within 250 µm. A 250-µm thick air gap will delay a shock wave by ~60 ns in this configuration, and significantly increase the impedance.

To correct this air gap problem we were careful to have the plates machined to the tightest reasonable tolerances, and then to apply massive insulating clamps to squeeze the surfaces together. We now know that these clamps caused additional problems.

D. Pressure induced breakdown.

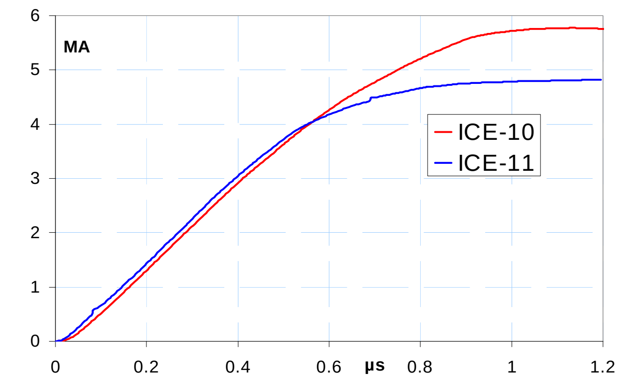
The Kapton insulation comprised of 20, 50-µm thick sheets between the transmission lines and, without the effects of sharp edges etc., was theoretically capable of withstanding ~280 kV. We were able to test the assembly to the approximate working voltage of the experiment, 120 kV successfully (although it might take many adjustments of the insulation placement to get it right). Before the application of the new Kapton switches (described above) we were always able to withstand 120 kV. However, with the new switches we were unable to withstand greater than 90 kV. After much experimentation we traced the problem to the application of the clamps. We experimented by taking small sections of Kapton and testing them up to 120 kV with the clamps loosely attached. When the clamp pressure was increased the maximum voltage before breakdown was only 90 kV. To correct this problem we carefully machined, and added extra insulation to, all the vulnerable edges between the transmission lines. Then only moderate and controlled pressure was applied with the clamps. This solved the problem. From then on we were able to test to 120 kV without any adjustments in insulation; it always worked on the first breakdown test.

IV. RECENT EXPERIMENTS

We have been able to fire two experiments with the new prototype system described above. Both of these shots were successfully performed to demonstrate the viability of the pulsed power system, since we had had so many problems up to this time. We therefore did not take EOS data on these shots. (One or two EOS experiments will be fired in the coming months of this year.)

1) Successful demonstration

The first successful tests of the prototype (ICE-10 and 11), comprised 1.27-cm wide, 2.54-cm long brass loads. The load currents and pressures for these two are shown in Fig. 6. The first test was fired conservatively, at a relatively low EFF voltage (100 kV), and the second shot



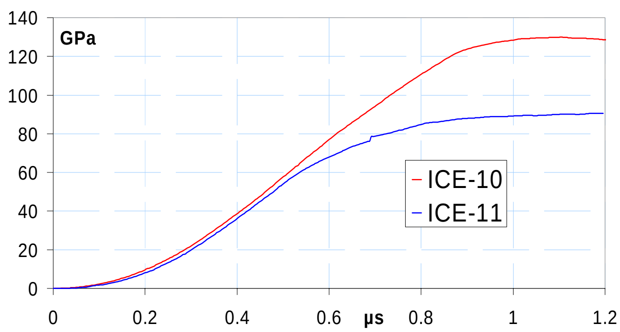


Figure 6A, B. Upper: Load currents; Lower: Calculated load pressures.

was fired closer to 120 kV. We had assembly problems with ICE-11 because there was a slight bow in the transmission line plates. We attempted to correct this by adding metal shims between the closing switches, but from the results this clearly increased the impedance of the switches and degraded their performance. Nevertheless, peak currents of 5.7 and 4.8 MA load currents were attained. (With the appropriate adjustments in EFF voltage and switch timing we expect to eventually obtain 7 MA load currents with the prototype.) The higher voltage of ICE-11 was offset by the higher impedance of the switches (with shims); but it can be seen that the initial dI/dt slope was higher.

These two shots (ICE-10 and 11) were fired without VISAR instrumentation, so we had to derive the pressure from calculations using $P_B = \frac{1}{2}\mu_0 J^2$. These data are shown in Fig. 6B. The peak pressures attained were 126 GPa (1.26 Mbar) and 90 GPa, with risetimes of 588 ns and 500 ns respectively. Both of these experiments would have been useful for generating high pressure EOS data if a VISAR had been used – so the viability of the technique has been proven. We were able to verify these pressure calculations by calculating the voltage across the loads and comparing it to measured values. These voltages were obtained by calculating the separation of the electrodes from the estimated isentropic brass EOS and the calculated pressure. From these we calculated the inductance, L, and the rate of change of inductance, dL/dt. Then using $V = {d(LI)}/{dt}$ we could calculate the voltage and compare to with the experiment; the agreement verified that the pressure profiles of Fig. 6B were correct.

V. SUMMARY

We have described the development of low jitter closing switches, and other modifications, and reported our progress towards developing a reliable prototype HEPP-ICE system, capable of producing EOS up to ~3 Mbar. Long term, we will work towards a 25-Mbar system based on the Ranchero flux compression generator (50 - 90 MA)[7], and operating at 500 kV.

VI. REFERENCES

1 J.R.Asay, "Isentropic Compression Experiments on the Z Accelerator," in Proc. APS Shock Compression of Condensed Matter, 1999, p.261.

[2] D.B. Reisman, et al. "Magnetically-driven Isentropic Compression Experiments on the Z-accelerator," JAP, 89(3), p.1625, 1 Feb. 2001.

[3] D.B. Reisman, et al., "Isentropic Compression of LX-04 on the Z Accelerator," Proc. APS Shock Compression of Condensed Matter, June 2001, Atlanta, GA.

[4] D.G. Tasker et al., "Isentropic Compression Of Metals, At Multi-Megabar Pressures, Using High Explosive Pulsed Power ," in Proc. 13th IEEE International Pulsed Power Conference, Las Vegas, NV, 2001, p.669.

[5] J.H. Goforth, "Analysis of Explosively Formed Fuse Experiments," this conference.

[6] J.H. Goforth, et al., "Procyon Experiments Utilizing Explosively-Formed Fuse Opening Switches," in Proc. Eighth IEEE International Pulsed Power Conference, San Diego, CA, 1991, p.273.

[7] J.H. Goforth, et al., "Ranchero Explosive Pulsed Power Experiments," in Proc. Twelfth IEEE Pulsed Power Conference, Monterey, CA, 1999.